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Model for the Propagation of Pulsed Surface
Polaritions with Quasi-Self-Induced Transparency

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HYPERBOLIC SECANT PULSES
TRANSVERSE PHASE OSCILLATIONS
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The possibility of quasi-self-induced transparency for the propagation of pulsed surface polaritions on a gas-solid interface is investigated. A theoretical model combining the optical Bloch and Maxwell equations is presented. The boundary conditions of the interface system lead to a closed relation between the laser pulse velocities in each of the two media. The behavior of transverse phase oscillations in hyperbolic secant pulses, due to the properties of the interface and the restriction of the pulse duration, are discussed. The treatment is extended to a slab (two-interface) configuration, where there is no restriction on the envelope of the pulsed
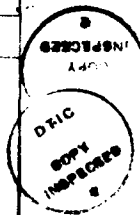
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Model for the Propagation of Pulsed Surface Polaritons

with Quasi-Self-Induced Transparency

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The possibility of quasi-self-induced transparency for the

propagation of pulsed surface polaritons on a gas-solid interface

is investigated. A theoretical model combining the optical Bloch

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properties of the interface and the restriction of the pulse dura-

tion, are discussed. The treatment is extended to a slab (two-

interface) configuration, where there is a restriction on the

envelope of the pulsed slab mode such that quasi-self-induced

transparency is no longer observed.

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I. Introduction

The development of sources of pulsed coherent radiation
(laser) has prompted investigations of the behavior of coherent
traveling waves interacting with media which have absorption bands
near or at the frequency of the applied pulse. Of particular inter-
est are resonant absorbing media characterized by two-level transi-
tions which are induced by optical radiation.[1] At the same time,
increasing attention has been paid to the problem of surface polar-
itons (SP), which, in a simple case, occur at a single interface
between two media, one having a negative dielectric (or magnetic)
permeability and the other a positive one. The SP propagate along
the interface and decay exponentially for directions normal to the
interface.[2] Under usual conditions, due to radiation absorption
or relaxation of the media, the SP propagating on the interface
would decay rapidly, where the traveling distance for infrared SP
are on the order of a cm.[3]

It is established that an optical pulse propagating through
an absorbing gas medium would be resonantly absorbed according to
Beer's law when its intensity is low. As the intensity of the
(coherent) laser radiation increases, the pulse may propagate through
the absorber gas as if it were transparent. This phenomenon, called
self-induced transparency, was predicted and demonstrated by McCall and
Hahn[4,5] and experimentally refined later.[6]

In the present paper, we shall study an interface system
comprised of a gas medium and a solid medium. In the next section
we predict and present an analysis of quasi-self-induced trans-
parency (quasi-SIT) for the propagation of SP on the interface of

a two-level atomic gas and an unspecified "surface-active" medium,
which is a solid material possessing a dielectric constant $\varepsilon_m(\omega)$
whose real part is negative near the frequency ω of interest. The
term "quasi" is used as a prefix to SIT since there is decay in the
solid medium through the imaginary part of ε_m. For the gas medium,
the imaginary part of ε_g plays a negligible role in the saturated
propagation governed by the nonlinear Bloch and Maxwell equations,
so that the propagation is lossless. The relation between the laser
pulse velocities in each media, which must match at the interface,
and phase oscillations associated with hyperbolic secant pulses are
revealed. In Section III the treatment is extended to a slab (two-
interface) configuration, where there is a restriction on the enve-
lope of the pulsed slab mode whereby quasi-SIT is no longer seen.
Section IV contains some final remarks.

II. Quasi-SIT Propagation of Pulsed SP in a Semi-Infinite Medium

Consider an interface system with two media separated at
$z = 0$ (see Fig. 1). Let a gas of two-level absorbers with dielectric
constant $\varepsilon_g(\omega)$ occupy the upper-half space $z > 0$. The lower-half
space $z < 0$ is filled by a second unspecified dielectric medium
characterized by an isotropic frequency-dependent dielectric function
$\varepsilon_m(\omega)$. For SP to exist, we require $\mathrm{Re}\,\varepsilon_m(\omega) < -\mathrm{Re}\,\varepsilon_g(\omega)\ (\approx -1)$

We shall consider plane waves propagating in the xz-plane as
shown in Fig. 1. The pulsed electromagnetic (EM) waves $\vec{E}_g$ and $\vec{E}_m$
propagating in the two media can be written as

$$\vec{E}_{g,m} = \hat{e}_{g,m} E_{g,m}(x_{g,m}, t) \exp[i(k_{g,m} x_{g,m} - \omega t)] + c.c., \qquad (2.1)$$

where ω is the frequency, $x_{g,m}$ is a space coordinate, $\vec{k}_{g,m}$ is the wave vector and $\hat{e}_{g,m}$ is the unit polarization vector perpendicular to $\vec{k}_{g,m}$. $E_{g,m}$ denotes the amplitude of the EM wave in the media and is assumed to be a slowly-varying function in space and time,

$$\partial E_{g,m}/\partial x_{g,m} \ll k_{g,m} E_{g,m} \text{ ,} \qquad (2.2)$$

$$\partial E_{g,m}/\partial t \ll \omega E_{g,m}. \qquad (2.3)$$

This assumption is justified on the basis that the shortest laser pulses one might work with in experiments are on the time scale of a fraction of a picosecond, whereas the carrier wavies have frequencies on the order of 10^{14} to 10^{15} sec^{-1} for the infrared and visible region of the spectrum.

We shall discuss separately the propagation behavior in each of the two media, beginning with the gas medium. The one-dimensional wave equation describing a plane wave propagating along the x_g-direction is

$$\left[\frac{\partial^2}{\partial x_g^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right] E_g(x_g,t) = \frac{4\pi}{c^2}\frac{\partial^2}{\partial t^2} P_g(x_g,t), \qquad (2.4)$$

where c is the vacuum speed of light and $P_g(x_g,t)$ is the polarization density. This density, characterized by the ensemble-averaged dipoles of the two-level atoms, can be obtained by solving the optical Bloch equations.[1] For a short pulse propagating in a dilute gas medium, we may neglect the damping rates in the Bloch equations.[1,4,5] The resulting lossless Bloch equations provide us with an interesting coherent pulse which is area- and shape-stable in propagation,[4,5]

$$E_g(\zeta_g) = \frac{2}{\kappa\tau}\text{sech}(\zeta_g/\tau). \qquad (2.5)$$

τ is the pulse duration, $\kappa = 2d/\hbar$ where d is the magnitude of the transition dipole of the absorber and

$$\zeta_g \equiv t - x_g/v_g. \tag{2.6}$$

v_g is the constant velocity of the laser pulse in the gas medium and can be evaluated by[1,4,5]

$$\frac{1}{v_g} - \frac{1}{c} = \frac{\alpha}{2\pi g(0)} \int d\Delta \, \frac{g(\Delta)}{\Delta^2 + (1/\tau)^2} \, , \tag{2.7}$$

where α is the absorption coefficient, $g(\Delta)$ is a normalized inhomogeneous broadening spectral density function and $\Delta = \omega_0 - \omega$ is the detuning of the laser with respect to the absorption frequency ω_0.

For the solid medium, the wave equation describing a plane wave propagating in the x_m-direction can be written as

$$[\frac{\partial^2}{\partial x_m^2} - \frac{\epsilon_m(\omega)}{c^2} \frac{\partial^2}{\partial t^2}] E_m(x_m, t) = 0, \tag{2.8}$$

where for a pulse with a slowly-varying amplitude

$$E_m(x_m, t) = \mathcal{E}_m(x_m, t) e^{i(k_m x_m - \omega t)} + c.c. \tag{2.9}$$

$\mathcal{E}_m(t, x_m)$ is the pulse envelope, ω is the wave frequency and k_m is the wave vector. Imposing the slowly-varying assumptions (2.2) and (2.3) on $\mathcal{E}_m$, we obtain the reduced Maxwell equation

$$k_m \frac{\partial \mathcal{E}(x_m, t)}{\partial x_m} + \frac{\omega \epsilon_m(\omega)}{c^2} \frac{\partial E_m(x_m, t)}{\partial t} = 0 \tag{2.10}$$

One of the solutions of Eq.(2.10) is

$$\mathcal{E}(x_m, t) = \mathcal{E}(\zeta_m) \tag{2.11}$$

where $E(\zeta_m)$ is any smooth function of ζ_m,

$$\zeta_m = t - x_m/v_m \qquad (2.12)$$

and v_m is the pulse velocity.

The infinite plane waves given by Eqs.(2.1) and (2.5) can be expressed in the xz-plane as

$$\vec{E}_{g,m} = \hat{e}_{g,m} E_{g,m}(\zeta_{g,m}) \exp[i(k_{(g,m)x}x \pm k_{(g,m)z}z - \omega t)] + c.c., \qquad (2.13)$$

where

$$\zeta_g = t - (k_{gx}x + k_{gz}z)/(k_g v_g), \qquad (2.14)$$

$$\zeta_m = t - (k_{mx}x - k_{mz}z)/(k_m v_m), \qquad (2.15)$$

and $k_{(g,m)x}$ and $k_{(g,m)z}$ are the x- and z-components of the wave vectors $\vec{k}_{g,m}$. We then impose the following boundary conditions at the interface defined by $z = 0$ (supposing no charge and current on the interface):

$$\hat{n} \cdot [\varepsilon_g(\omega)\vec{E}_g - \varepsilon_m(\omega)\vec{E}_m] = 0 \qquad (2.16)$$

$$\hat{n} \times [\vec{E}_g - \vec{E}_m] = 0, \qquad (2.17)$$

where $\hat{n}$ is the unit vector along the positive z-axis as shown in Fig. 1. This gives the form of the dispersion relation for the pulsed SP as

$$k_x(\omega) \equiv k_{gx}(\omega) = k_{mx}(\omega) = \frac{\omega}{c}\left[\frac{\varepsilon_g(\omega)\varepsilon_m(\omega)}{\varepsilon_g(\omega) + \varepsilon_m(\omega)}\right]^{1/2}, \qquad (2.18)$$

and quite interesting to note, there is a closed relation between the pulse velocities in the two media given as

$$v_g k_g / k_x = v_m k_m / k_x. \tag{2.19}$$

We define $v_x \equiv v_g k_g / k_x$, the x- and z-components of the amplitudes of the EM waves in the two media as

$$E_{gx}(t-x/v_x) = E_{mx}(t-x/v_x) \tag{2.20}$$

$$E_{gz}(t-x/v_x) = - \frac{\varepsilon_m(\omega)}{\varepsilon_g(\omega)} E_{mz}(t-x/v_x). \tag{2.21}$$

Eqs.(2.20) and (2.21) mean that once the hyperbolic secant pulse is prepared in the gas medium, the envelope of the field amplitude in the solid medium will be a hyperbolic secant profile as well.

Eqs.(2.12) and (2.19) lead to a restriction on the constant pulse velocity of the hyperbolic secant pulse in the gas medium, namely,

$$v_g = \omega/k_g \approx c. \tag{2.22}$$

This requirement is different from what one usually expects of SIT pulses in homogeneous gas media, where the pulse velocity v_g can be much smaller than c.[4,5,6] For a short laser pulse with duration τ much less than the inhomogeneous lifetime T^*, Eq.(2.7) takes the form

$$\frac{1}{v_g} - \frac{1}{c} = \frac{\alpha \tau^2}{2T^*} \tag{2.23}$$

The requirement of $v_g \approx c$ leads to the restriction on the pulse duration that

$$\tau << (2T^*/\alpha)^{1/2}, \tag{2.24}$$

which is a much milder condition than $\tau \ll T^*$. A typical value of
T^* in the gas medium, originating from the Doppler effect, would
be around a nanosecond.[6] Hence, a laser pulse which could generate
quasi-SIT propagation for SP on the interface (i.e., lossless propa-
gation in the gas medium but decay in the solid medium) must be
substantially less than a nanosecond.

We can now write the EM fields in the two media, obtained
by combining the Maxwell and Bloch equations, as

$$\vec{E}_g = \frac{2}{\kappa\tau}(-\frac{k_{gz}}{k_g},0,\frac{k_x}{k_g})\operatorname{sech}\left(\frac{t-x/v_x-z/v_{gz}}{\tau}\right)\exp[i(k_x x+k_{gz}z-\omega t)]+c.c.$$

$$(2.25)$$

$$\vec{E}_m = \frac{2}{\kappa\tau}(-\frac{k_{mz}}{k_m},0,-\frac{k_x}{k_m})\operatorname{sech}\left(\frac{t-x/v_x+z/v_{mz}}{\tau}\right)\exp[i(k_x x-k_{mz}z-\omega t)]+c.c.$$

$$(2.26)$$

When $\operatorname{Re}\epsilon_m < -\operatorname{Re}\epsilon_g$, $\vec{E}_{g,m}$ decays in the direction normal to the inter-
face, and

$$v_x \equiv v_g k_g/k_x = v_m k_m/k_x \qquad\qquad (2.27)$$

$$v_{gz} \equiv v_g k_g/k_{gz} \qquad\qquad (2.28)$$

$$v_{mz} \equiv v_m k_m/k_{mz} \qquad\qquad (2.29)$$

It is interesting to note from the above expressions for the EM
fields that the quasi-SIT propagation of SP occurs along the inter-
face with a constant velocity v_x (less than c), but that exponential
decay with an oscillatory phase behavior occurs normal to the inter-
face. Such oscillations would be a unique feature for a heterogeneous
system (with $\operatorname{Re}\epsilon_m < -\operatorname{Re}\epsilon_g$) and cannot be found in a homogeneous
system.

In order to understand the effect of the dielectric constants on these oscillations, we consider the z-components of the SP as derived from Eqs.(2.27) and (2.28),

$$E_{gz} = \frac{8}{\kappa\tau} \frac{e^{-\alpha_g z}}{(1-\epsilon_g/|\epsilon_m|)^{1/2}} [e^T\cos(\beta_g z-\Omega)+e^{-T}\cos(\beta_g z+\Omega)]/D_g \qquad (2.30)$$

$$E_{mz} = \frac{8}{\kappa\tau} \frac{e^{-\alpha_m|z|}}{(|\epsilon_m|/\epsilon_g-1)^{1/2}} [e^{-T}\sin(\beta_m|z|-\Omega)+e^T\sin(\beta_m|z|+\Omega)/D_m, \qquad (2.31)$$

where $\alpha_{g,m}$ is the imaginary part of $k_{(g,m)z}$ and

$$T = (t-x/v_x)/\tau \qquad (2.32)$$

$$\beta_{g,m} = 1/(\tau|v_{(g,m)z}|) \qquad (2.33)$$

$$\Omega = k_x x - \omega t \qquad (2.34)$$

$$D_{g,m} = e^{2T} + e^{-2T} + 2\cos(2\beta_{g,m}z). \qquad (2.35)$$

The propagation of the above z-components, normalized to the peak value of E_{gz} with $\epsilon_g = 1$ and $\epsilon_m = -10$, is shown in Fig. 2 (we are taking the dielectric constants to be real). The large $|\epsilon_m|$ cases in Parts (A) and (B) correspond , for example, to SP propagating along a diatomic cubic crystal surface with frequency near the transverse optical phonon frequency, $\omega \gtrsim \omega_{t0}$, or a metal surface with frequency far less than the plasma frequency, $\omega << \omega_p$. The smaller $|\epsilon_m|$ cases in Parts (C) and (D) correspond to SP propagating along a diatomic cubic surface with frequency near the longitudinal optical phonon frequency of the crystal, $\omega \lesssim \omega_{\ell 0}$, or a metal surface

with frequency near the plasma frequency, $\omega \lesssim \omega_p$.[7] We note that the behavior of the SP is characterized not only by the phase factor Ω [compare Parts (A) and (B)], but also by the dielectric constant ε_m [compare Parts (C) and (D)]. The decay of the SP in the solid medium is faster than in the gas medium, since $|\varepsilon_m| > \varepsilon_g$ and $\alpha_m = |\varepsilon_m|\alpha_g$.

III. Propagation of Pulsed SP in a Slab (Two-Interface) Configuration

We now extend our treatment to the situation of two interfaces, where for simplification we assume each dielectric media to be optically isotropic and hence neglect any effects of spatial dispersion. We restrict ourselves to a symmetric slab configuration, i.e., where the media adjoining the slab are identical, although the extension to non-symmetric cases is straightforward. We also take the point of view that there is one EM wave in each of the media adjoining the slab, and hence two EM waves in the slab medium, i.e., a pair of EM waves associated with each interface between the optically-isotropic media (see Fig. 3).

Let us consider a pulsed interface mode propagating in the x-direction along a slab of thickness d parallel to the xz-plane. As seen in Fig. 3, the interface between medium 1 and the slab (medium 2) is located at $z = 0$, and the interface between medium 3 and the slab is at $z = d$. Invoking the assumption of a slowly-vatying pulse envelope, (2.2) and (2.3), we can express the electric fields in the three media as

$$\vec{E}_1 = \hat{e}_1 E_1(\zeta_1) \exp[i(k_{1x}x - k_{1z}z - \omega t)],$$

$$z < 0 \qquad\qquad (3.1)$$

$$\vec{E}_2 = E_2^a + E_2^b$$

$$= \hat{e}_2^a E_2^a(\zeta_2^a) \exp[i(k_{2x}x + k_{2z}z - \omega t)]$$

$$+ \hat{e}_2^b E_2^b(\zeta_2^b) \exp[i(k_{2x}x - k_{2z}z' - \omega t)],$$

$$0 < z < d, \quad z' = z - d < 0 \qquad (3.2)$$

$$\vec{E}_3 = \hat{e}_3 E_3(\zeta_3) \exp[i(k_{3x}x + k_{3z}z' - \omega t)]$$

$$z' > 0. \qquad (3.3)$$

$E_1(\zeta_1)$ and $E_2(\zeta_2^a)$ are the amplitudes of $\vec{E}_1$ and $\vec{E}_2$, respectively, at the $z = 0$ interface, E_2^b and E_3 are the amplitudes of $\vec{E}_2^b$ and $\vec{E}_3$ at the $z = d$ interface and

$$\zeta_1 = t - (x\cos\alpha_1 - z\sin\alpha_1)/v_1, \quad z < 0 \qquad (3.4)$$

$$\zeta_2^a = t - (x\cos\alpha_2 + z\sin\alpha_2)/v_2, \quad 0 < z < d \qquad (3.5)$$

$$\zeta_2^b = t - (x\cos\alpha_2 - z'\sin\alpha_2)/v_2, \quad -d < z' < 0 \qquad (3.6)$$

$$\zeta_3 = t - (x\cos\alpha_3 + z'\sin\alpha_3)/v_3. \quad z' > 0 \qquad (3.7)$$

k_{ix} and k_{iz} (i = 1,2,3) are the wave vector components parallel and perpendicular to the interfaces, respectively. For surface wave (polariton) propagation, the real part of ε_1 must be negative while the real part of ε_2 is positive, or vice versa.

Imposing the bondary conditions of Eqs.(2.16) and (2.17) at each interface, we arrive at the following relations:

$$-\frac{\varepsilon_1}{k_1} E_1\left(t - \frac{xk_x}{v_1 k_1}\right) = \frac{\varepsilon_2}{k_2}\left[E_2\left(t - \frac{xk_x}{v_2 k_2}\right) - E_2\left(t - \frac{xk_x + dk_{2z}}{v_2 k_2}\right)\exp(ik_{2z}d)\right] \qquad (3.8)$$

$$-\frac{k_{1z}}{k_1} E_1\left(t - \frac{xk_x}{v_1 k_1}\right) = \frac{k_{2z}}{k_2}\left[E_2\left(t - \frac{xk_x}{v_2 k_2}\right) + E_2\left(t - \frac{xk_x + dk_{2z}}{v_2 k_2}\right)\exp(ik_{2z}d)\right], \qquad (3.9)$$

where

$$k_x = k_{1x} = k_{2x} = k_{3x}.$$ (3.10)

As compared to the case of continuous wave operation,[2,8] Eqs.(3.8) and (3.9) lead to an extra condition for the matching of waves at the interfaces, namely,

$$\frac{\varepsilon_2 k_{1z} + \varepsilon_1 k_{2z}}{\varepsilon_2 k_{1z} - \varepsilon_k k_{2z}} \frac{E_2(t - x/v_{2x})}{E_2(t - x/v_{2x} - d/v_{2z})} = e^{ik_{2z}d},$$ (3.11)

where

$$v_{1x} \equiv \frac{v_1}{k_x/k_1}$$ (3.12)

$$v_{2x} \equiv \frac{v_2}{k_x/k_2}$$ (3.13)

$$v_{2z} \equiv \frac{v_2}{k_{2z}/k_2}.$$ (3.14)

To satisfy Eq.(3.11) at any time t (t > 0) and any spatial point x on the interfaces, the pulse envelope for the slab mode, E_2, must be prepared as

$$E_2(t - x/v_{2x} - d/v_{2z}) = E_2(t - x/v_{2x}) f(d/v_{2z}),$$ (3.15)

where $f(d/v_{2z})$ is independent of x and t. For example, for an exponentially decaying pulse (i.e., a field which is turned on quickly and then decays exponentially) given as

$$E_2(t - x/v_{2x}) = e^{-(t - x/v_{2x})},$$ (t > 0) (3.16)

Eq.(3.11) reduces to the dispersion relation

$$\frac{\varepsilon_2 k_{1z} + \varepsilon_1 k_{2z}}{\varepsilon_2 k_{1z} - \varepsilon_1 k_{2z}} = e^{i(k_{2z} + 1/v_{2z})d}.$$ (3.17)

Combining Eqs.(3.8), (3.9) and (3.15), we see another requirement
for pulsed surface mode propagation in the symmetric slab configura-
tion,

$$v_{1x} = v_{2x}, \tag{3.18}$$

which is similar to Eq.(2.19) for the single-interface case.

Let us suppose the slab to be filled by a two-level atomic gas,
wherein the hyperbolic secant envelope $E_2(\zeta) = \text{sech}(\zeta) = 2/(e^{-\zeta}+e^{\zeta})$
does not satisfy Eq.(3.15). The condition of (3.15) means that the
pulses coming from the two interfaces inside the slab must combine
to create a single pulse to match the pulses propagating in the
media surrounding the slab (see Fig. 4). This is a strong restric-
tion on the pulse envelope, and hence quasi-SIT does not exist as
in the case of a single interface.

In the limit of continuous-wave operation, i.e., $E_1 \approx$ constant
and $E_2 \approx$ constant, Eq.(3.11) reduces to a well-known dispersion for
the slab configuration,[2,8]

$$\frac{\varepsilon_2 k_{1z}+\varepsilon_1 k_{2z}}{\varepsilon_2 k_{1z}-\varepsilon_1 k_{2z}} = e^{ik_{2z}d}. \tag{3.19}$$

For a very thick slab $[d \gg I_m(1/k_{2z})]$, the above expression reduces
to a single-interface relation,

$$\frac{k_{1z}}{k_{2z}} = -\frac{\varepsilon_1}{\varepsilon_2}. \tag{3.20}$$

IV. Summary and Final Remarks

Through a model consisting of a single gas-solid interface,
we have considered the possible existence of SP with quasi-SIT.
For generating such SP, the velocities of hyperbolic secant pulses
must match on the interface. In this regard, it is suggested that

the pulse duration of the coherent light has to be substantially less than a nanosecond. An interesting behavior of transverse phase oscillations in the hyperbolic secant waves, caused by the interface effect, is revealed. Such a new phenomenon is not found in a homogeneous gas medium.

To experimentally check the existence of SP with quasi-SIT, the SF_6-Al interface with CO_2 laser pulses might be a good candidate. Using 10.6-μm CO_2 laser pulses, Patel and Slusher[9,10] have observed SIT in SF_6. Since the dielectric constant of Al in this frequency region is negative, we anticipate SP with quasi-SIT.

Concerning the rising intensity of a coherent EM wave, it is interesting to note that as the field energy has been confined to a thin region near the surface, the intensity of SP should increase by a factor of 10 to 100 compared to that of the incident laser beam.[3,11] Based on the optical "area theorem" in SIT,[1,4,5] SP with quasi-SIT may be further increased by the choice of an appropriate "pulse area". For example, if an intense short pulse with area $A = 3\pi$ is injected into a gas medium, it will tend toward $A = 2\pi$ as it propagates and the pulse intensity will be amplified by the absorbing medium by a factor of 9/4.

The extension of pulsed SP propagation to a slab (two-interface) configuration has been considered. For the pulsed slab mode to occur, in addition to the pulse velocity matching requirement there is a restriction on the pulse envelope function of the slab mode so that quasi-SIT is no longer observed. Such a restriction is peculiar to pulsed surface wave propagation and does not apply to the continuous-wave case.

Acknowledgments

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Figure Captions

1. SP propagation on an interface. The wave vectors $\vec{k}_{g,m}$ and unit vectors $\hat{e}_{g,m}$ and $\hat{n}$ are indicated. When $\mathrm{Re}\,\varepsilon_m(\omega) < -\mathrm{Re}\,\varepsilon_g(\omega)$ and $\mathrm{Re}\,\varepsilon_g > 0$, SP will occur on the interface.

2. The propagation of normalized SP [Eqs.(2.32) and (2.33)] in the gas ($z > 0$) and solid ($z < 0$) media for real dielectric constants, where $\varepsilon_g = 1$ and $(\varepsilon_m,\Omega) =$ (A) $(-10,0)$, (B) $(-10,\pi/2)$, (C) $(-5,0)$ and (D) $(-2,\pi/2)$. Here we have used $T = 0.5$, $\tau = 2$ picoseconds and z in units of c/ω.

3. SP propagation in a slab configuration. The wave vectors $\vec{k}_i$ and unit vectors $\hat{e}_i$ ($i = 1,2,3$) in the three media are indicated.

4. Schematic diagram of the conditions of Eqs.(3.8) and (3.9), where pulses from both interfaces must combine to form a single pulse to match the pulses in the media surrounding the slab. For a thin enough slab, there is a delay between the pulses given by $\zeta_d = d/v_{2z}$. The quantities ζ_1 and ζ_2 are defined as $\zeta_i = t - x/v_{ix}$.

x

z

x_g

$\vec{K}_g$

$\hat{e}_g$

$\hat{n}$

$\vec{K}_m$

x_m

$\hat{e}_m$

Fig.1

(A)

SOLID   GAS

(B)

Z

Fig. 2 (A)(B)

Fig. 2 (c,d)

3

2

1

$\vec{K}_3$

$\vec{K}_2^b$

$\vec{K}_2^a$

$\vec{K}_1$

$\hat{e}_3$

$\hat{e}_2^a$

$\hat{e}_2^b$

$\hat{e}_1$

d

x

z

$\hat{n}$

Fig. 3

$E_1(\zeta_1)$

1-2
INTERFACE

$E_2(\zeta_2)$

$E_2(\zeta_2-\zeta_d)$

ζ_d

1-2
INTERFACE

2-3
INTERFACE
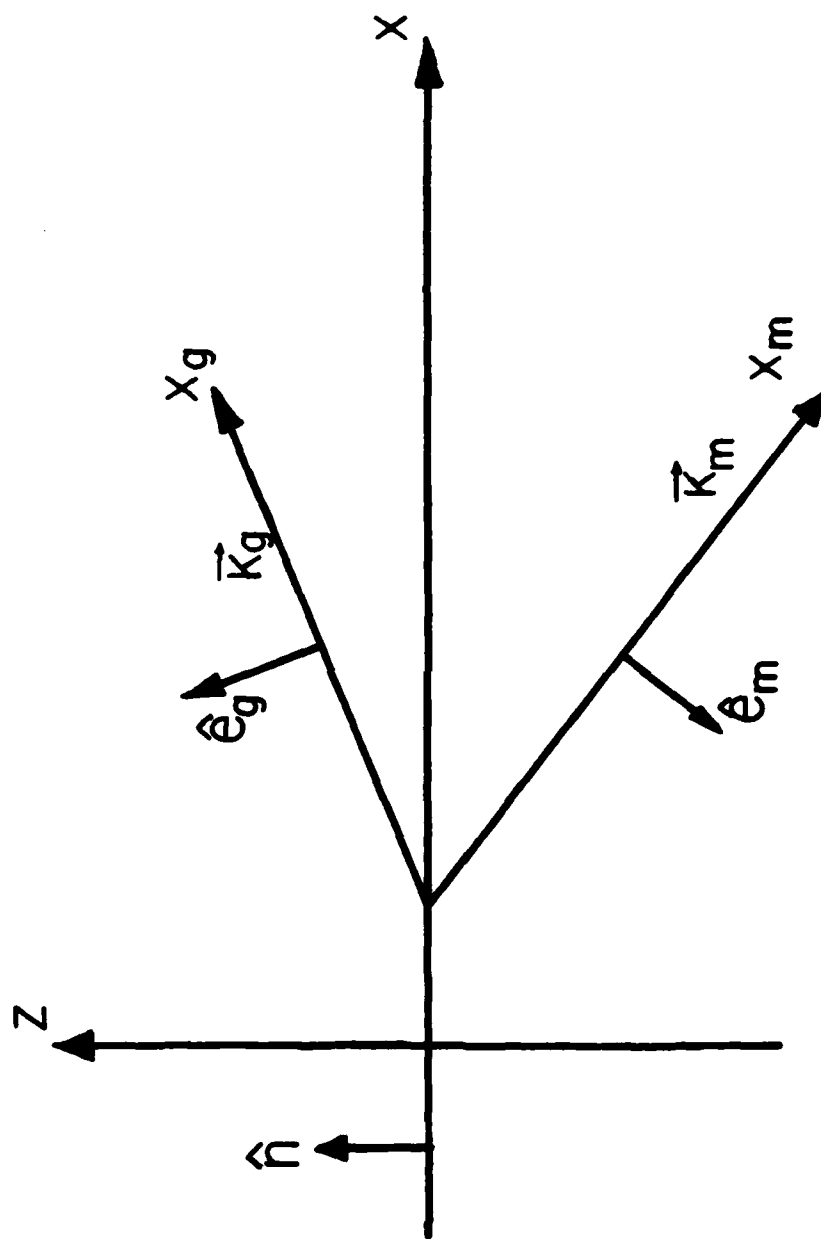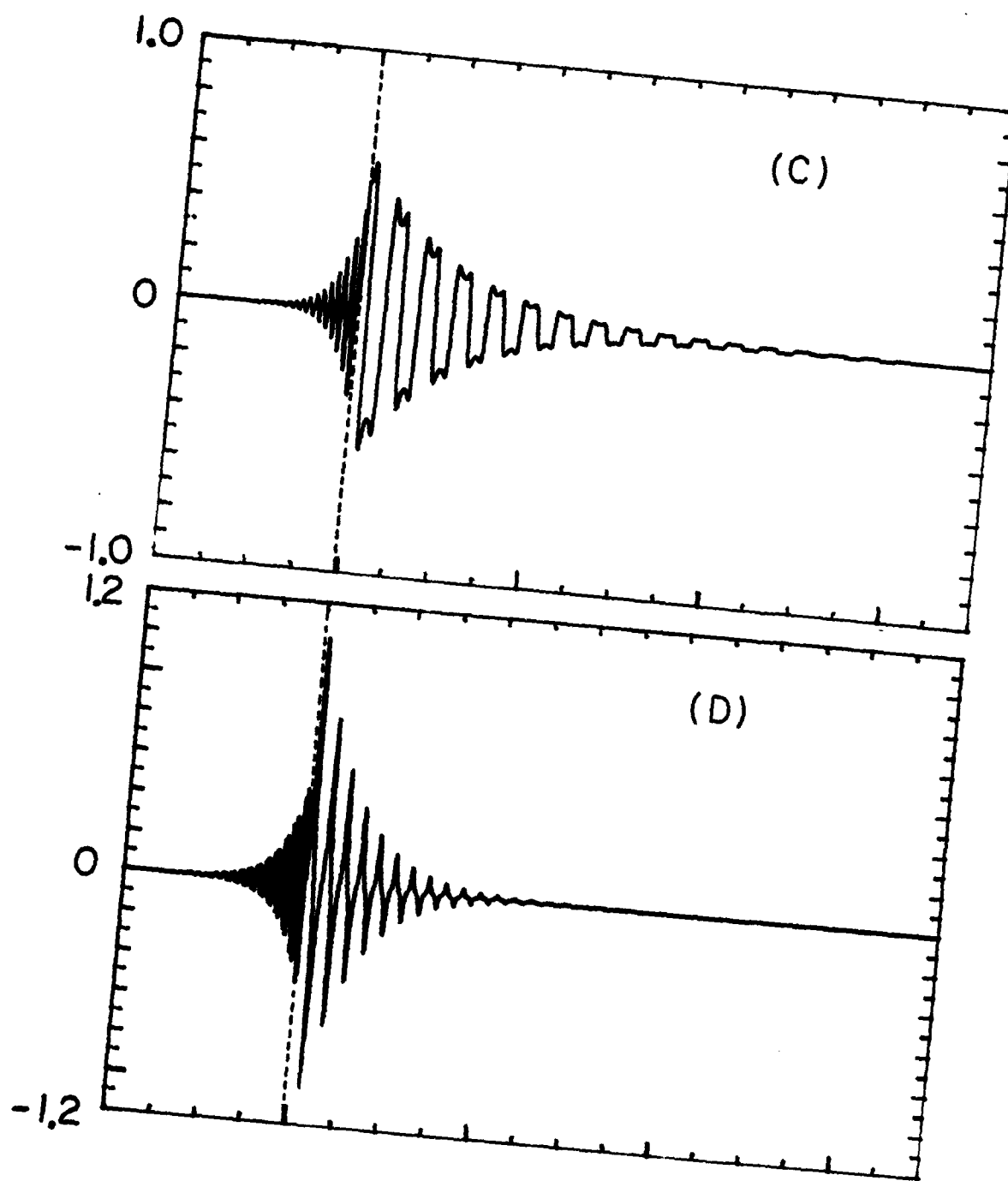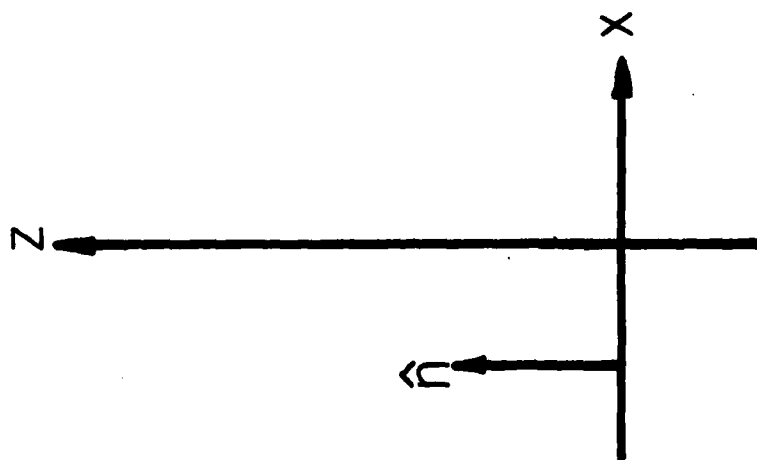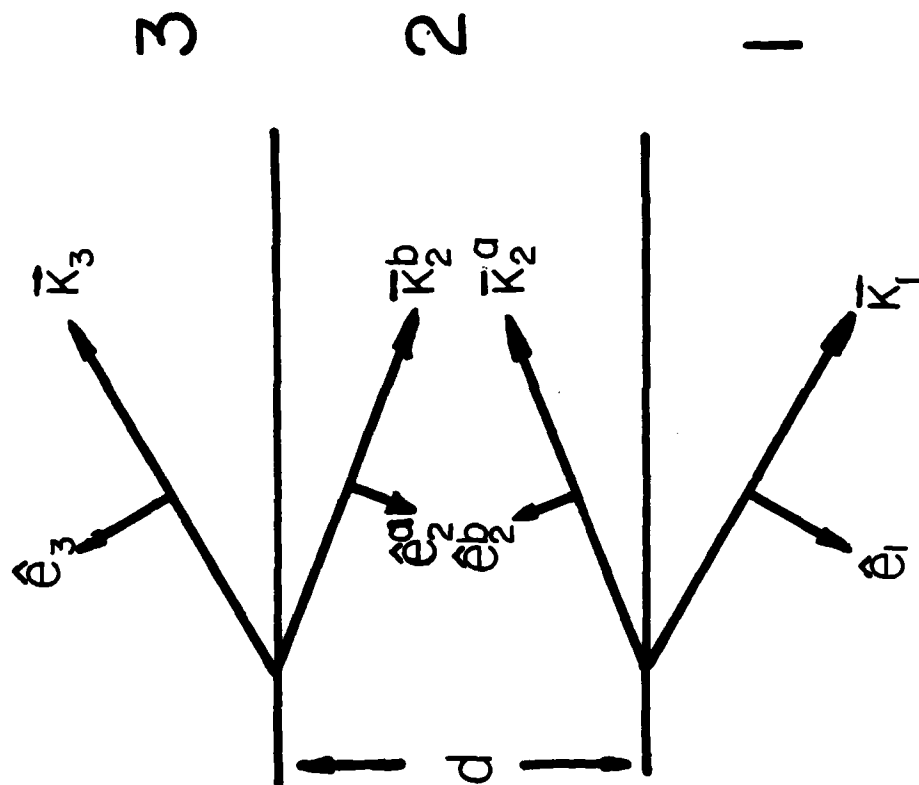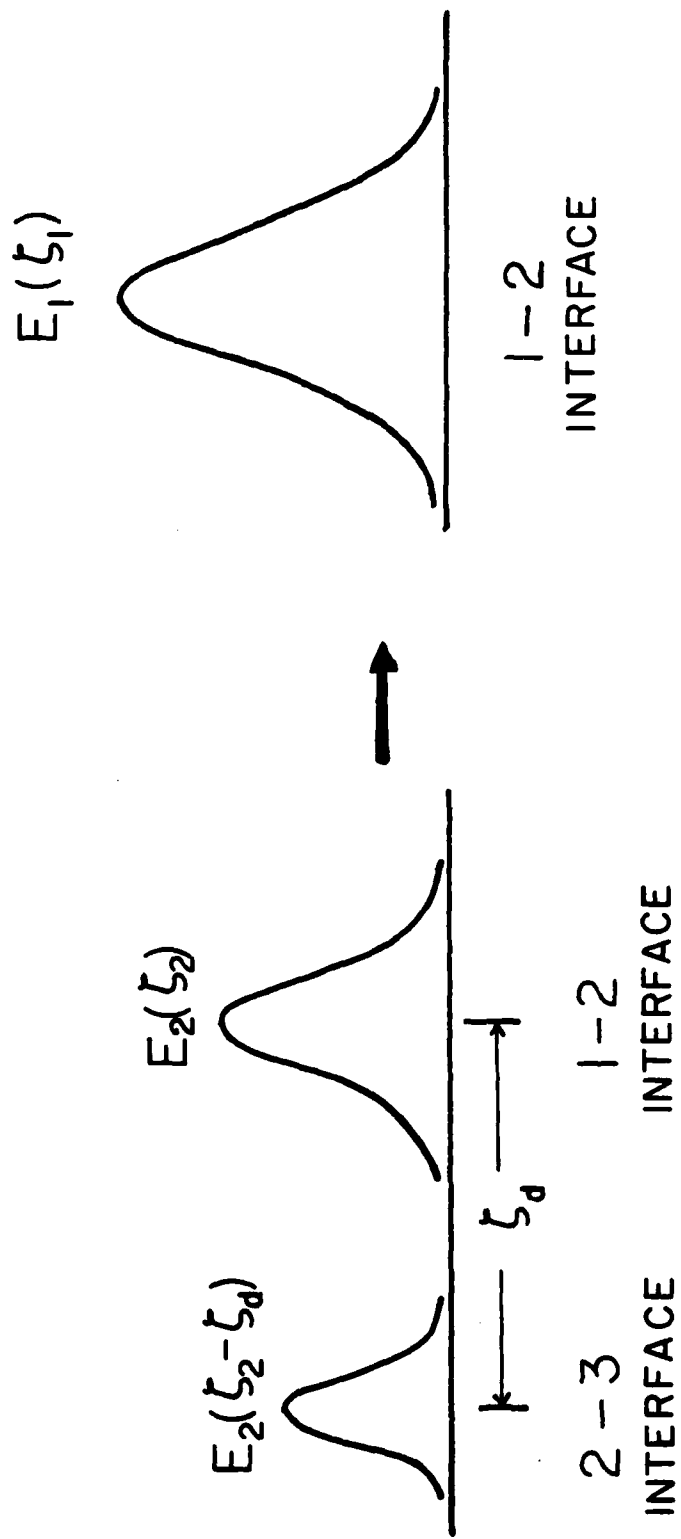
Fig. 4.

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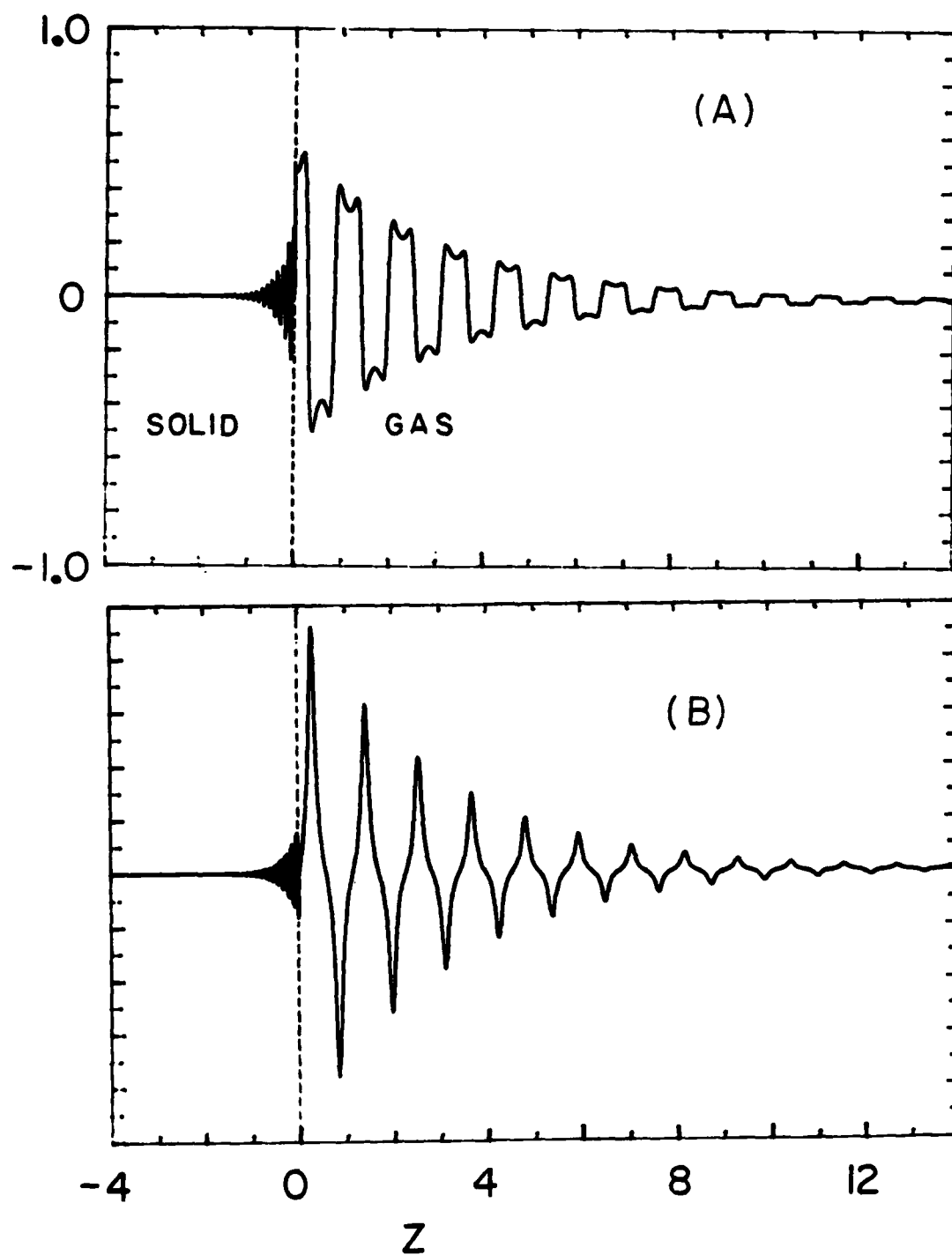|	No. Copies		No. Copies
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